The Rest of Newton's Apple

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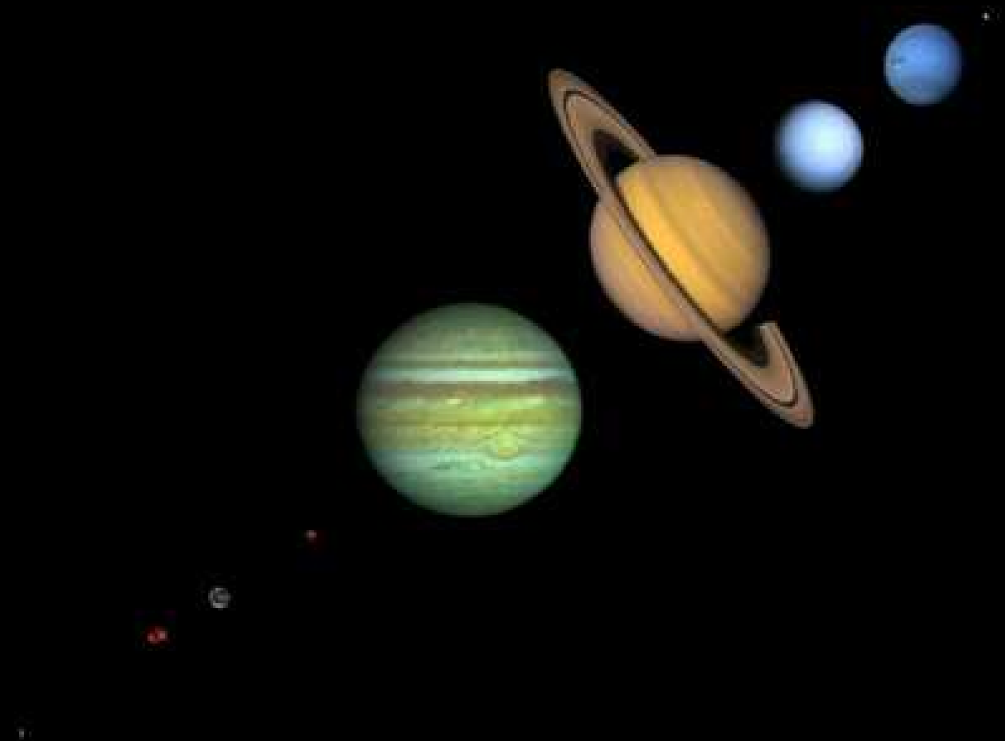
December 9, 2008

Newtonian gravity: unified motions of apples and planets.

Profound implication:

Experiments can explain the universe.



General Relativity (GR):

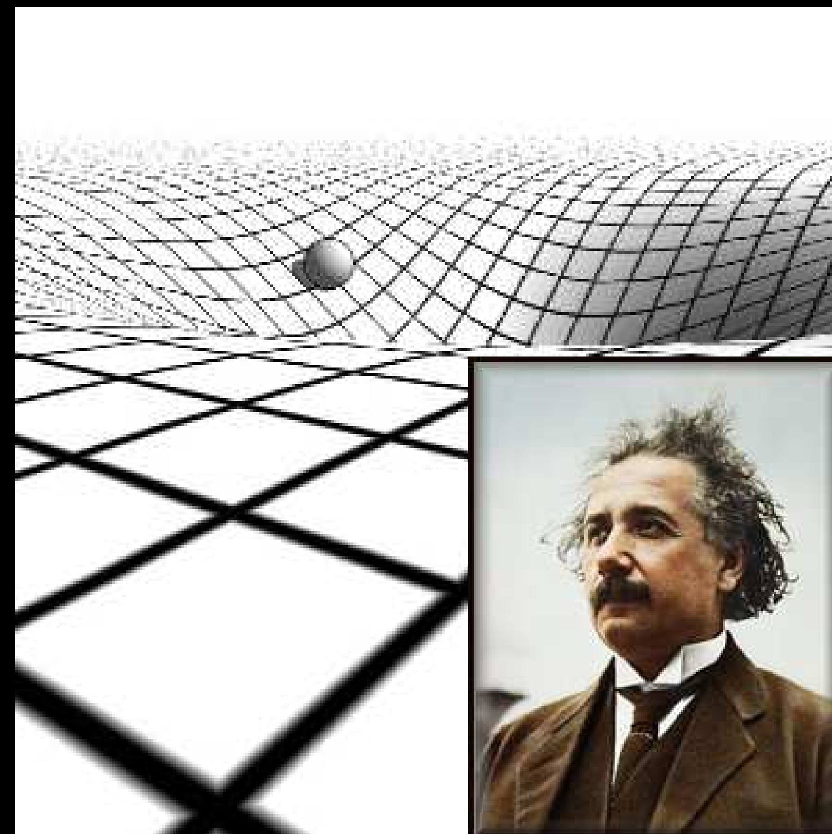
- Spacetime curved by matter/energy.

Sun

- Gravitational Force $\longrightarrow$ Geodesic.

Earth's Orbit

- Basis of modern cosmology.



Einstein's equations:

Curvature $$\mathcal{G}_{\mu\nu} = 8\,\pi\,G_N\,\mathcal{T}_{\mu\nu}$$ Energy Distribution

G_N Newton's constant, $\mu, \nu = 0, 1, 2, 3$ (spacetime).

Everyday life:

Gravity and Electromagnetism (EM).

Electromagnetism: “electricity” and “magnetism” unified (Maxwell)

Falling Apple: Gravity

Apple on the ground: EM

- Atoms in the apple and ground: EM forces stop the fall.
- Atom: Nucleus (p and n) and electrons; Quantum Mechanics.
- Nuclear forces: weak and strong, not everyday, microscopic.
- Weak and EM forces $\longrightarrow$ Unified Electroweak Theory.

Summed up in the Standard Model of particle physics.

The Standard Model (SM):

Most precise description of microscopic physics.

- **Gauge symmetry:** $SU(3)(\text{strong}) \times SU(2) \times U(1)(\text{electroweak})$.

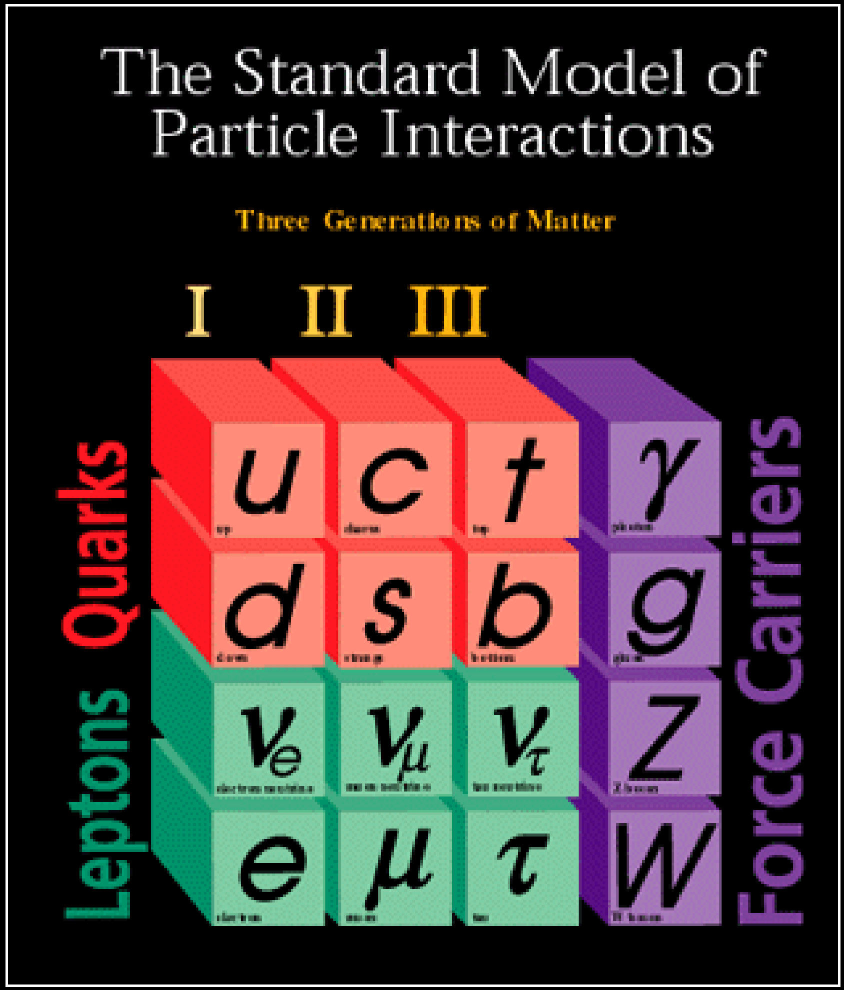
- **Elementary fermions (spin-1/2):**

Quarks $(+2/3, -1/3)$: Strong interactions

Leptons $(0, -1)$: No strong interactions

- **Mediators: Gauge Fields (spin-1).**

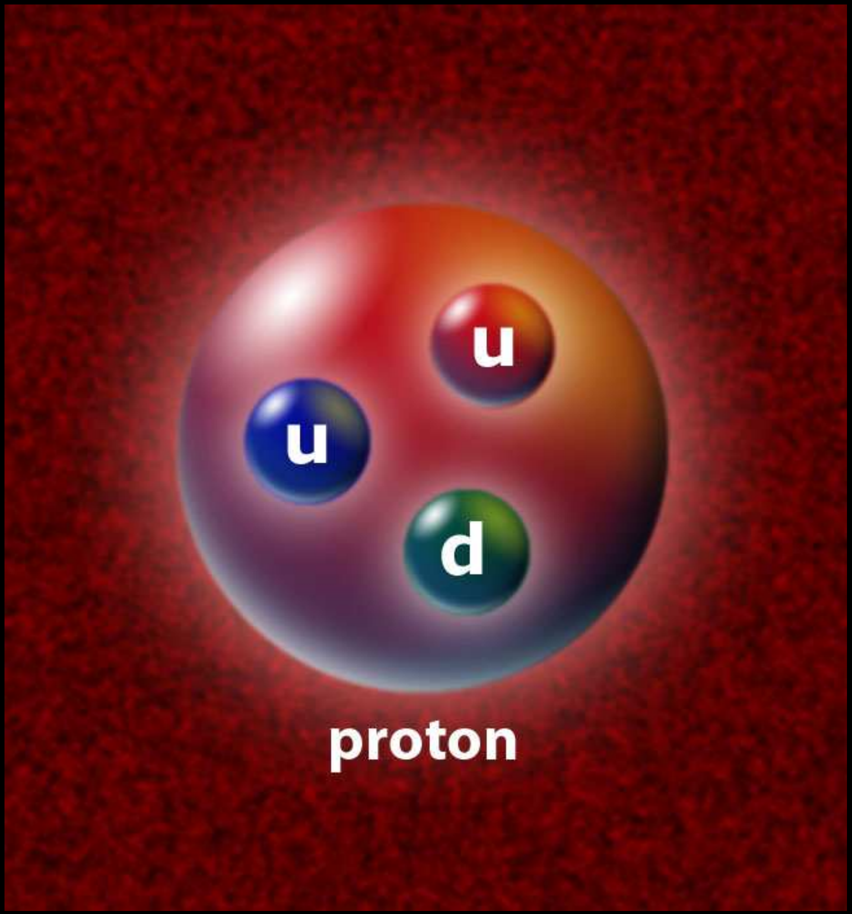
Generalized photons

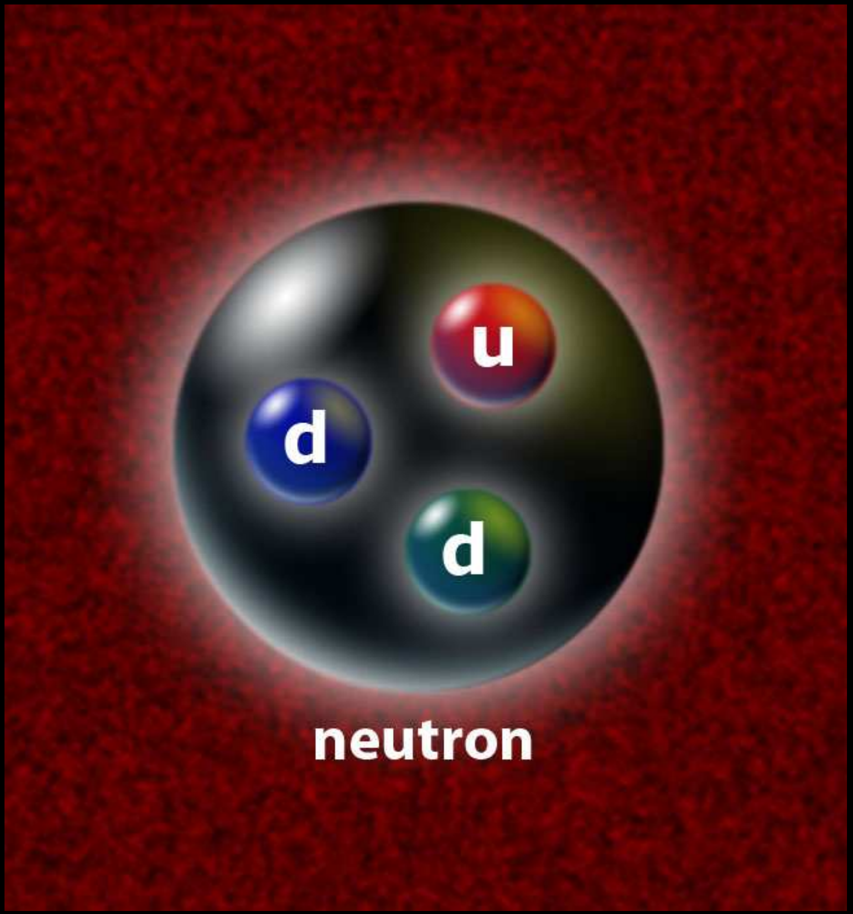


Strong Interactions [$SU(3)$ (QCD)]:

- Short-ranged, confined beyond nuclear distances $\sim 10^{-15}$m.

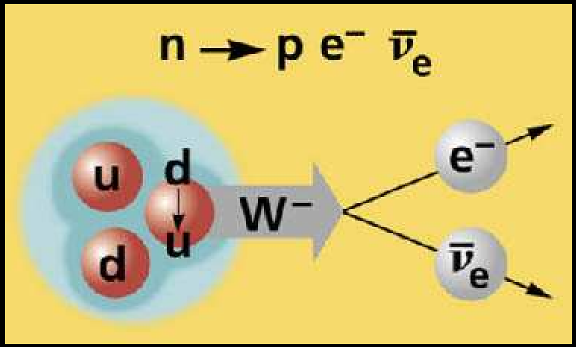
- Gluons (g) bind quarks into **hadrons**: p, n, ...





Electroweak Interactions $[SU(2)_L \times U(1)_Y]$:

- Spontaneously broken to EM



$\Rightarrow$ Massive $W^{\pm}\,(80.4\ \mathrm{GeV}/c^2)$, $Z^0\,(91.2\ \mathrm{GeV}/c^2)$

Short-ranged: $\Delta x \sim c\,\Delta t \sim \hbar/(mc) \sim 10^{-18}$ m.

- EM: $U(1)_{EM}$ (QED)

Long-ranged (everyday life).

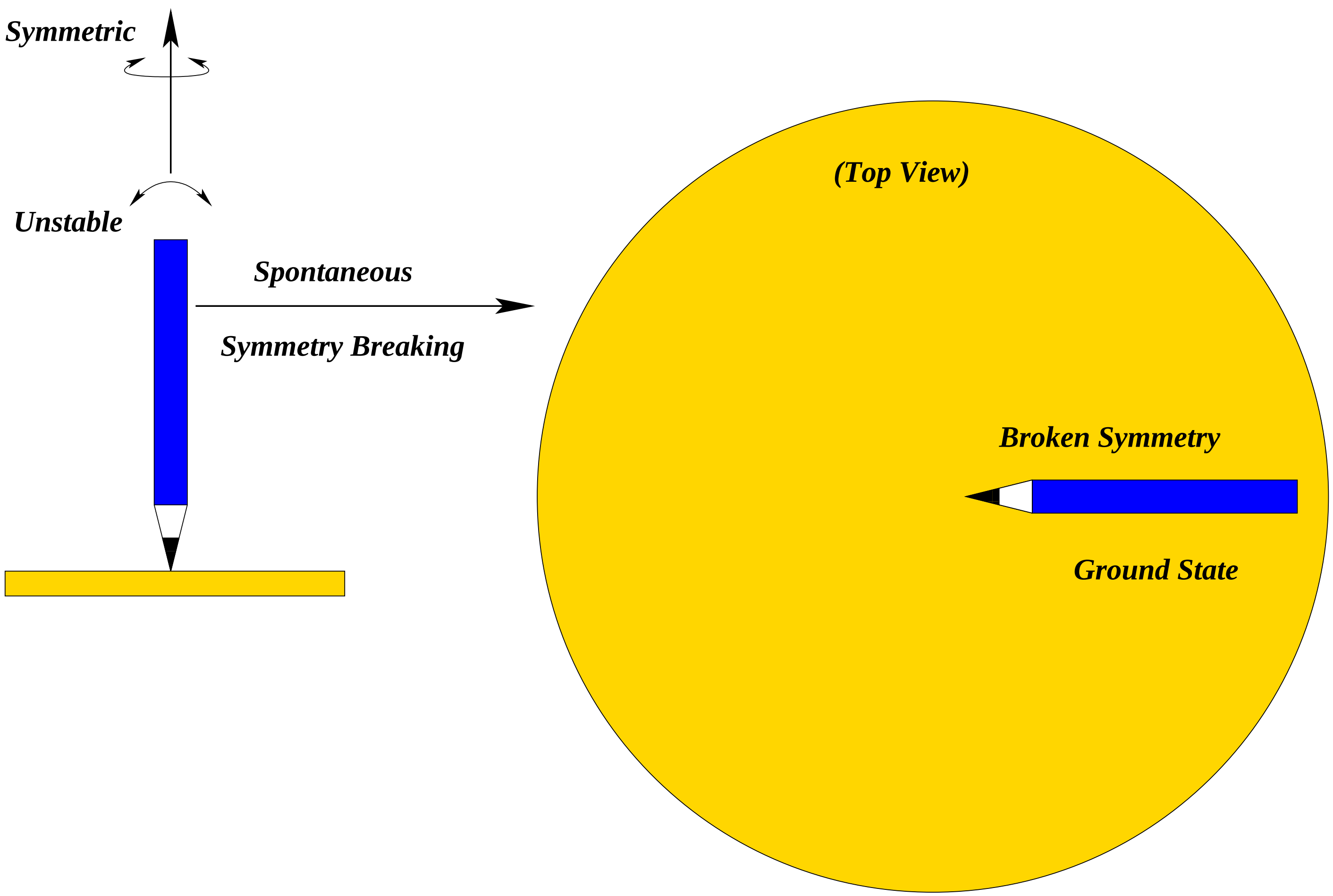
Massless photon, γ.

Great, but what is a spontaneously broken symmetry?

Tabletop Spontaneous Symmetry Breaking

A pencil, standing on its tip: unstable, falls to its "ground state".

- **Underlying theory: rotationally symmetric, no preferred direction.**
- **The pencil spontaneously picks an orientation, breaks the symmetry.**



What breaks electroweak symmetry?

<u>We do not know for sure.</u>

Tevatron at Fermilab
Beam energy: 2×980 GeV
(Ongoing)
Circumference (km): 6.28

LHC at CERN
Beam energy: 2×7000 GeV
(Restart 2009)
Circumference (km): 26.659

Electroweak Symmetry Breaking in SM

- Higgs (H) boson condensation $\langle H \rangle \neq 0$.

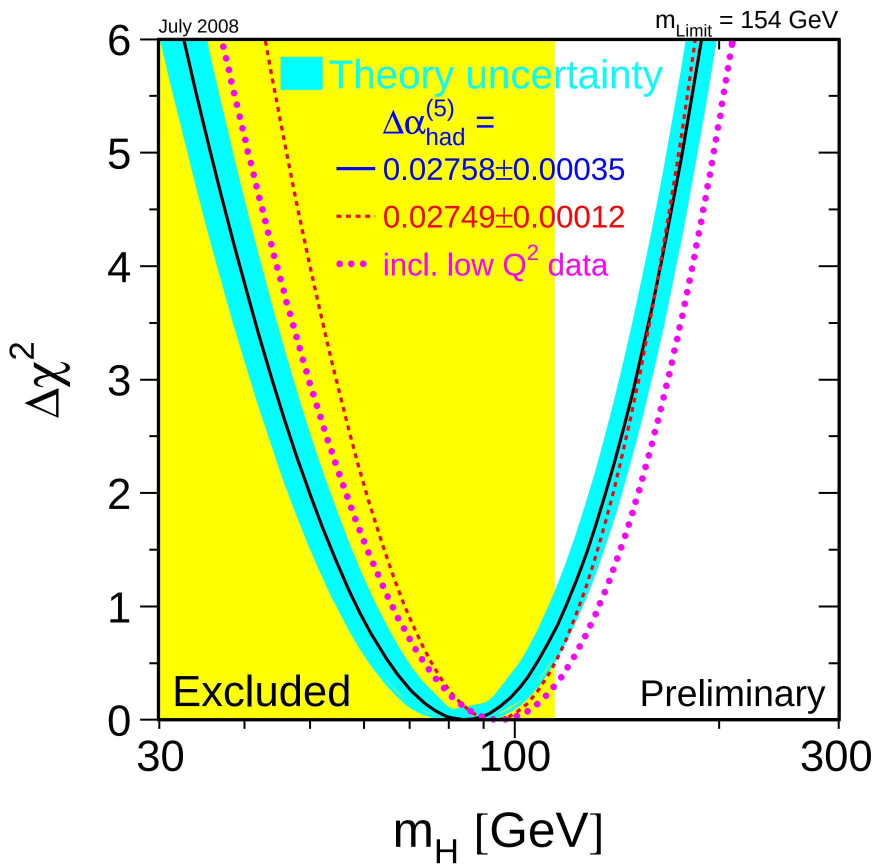
- Mass from interactions with $\langle H \rangle \neq 0$:

$m_W, m_Z \sim \langle H \rangle$

Charged fermion Flavor

$m_t/m_e \sim 10^5$! (Why?)

- $m_\nu = 0$.



⋆ *Aside:* Visible mass in universe mostly from QCD.

SM together with GR: A great success!

Nearly all measurements in agreement with SM+GR.

However, SM not the entire picture.

- **Experimental evidence:**

$m_\nu \neq 0$, **dark matter, . . .**

- **Theoretical hints:**

Why is gravity so weak? (This talk)

Why is the neutron EDM so small ($\bar{\theta} \lesssim 10^{-10}$)?.

. . .

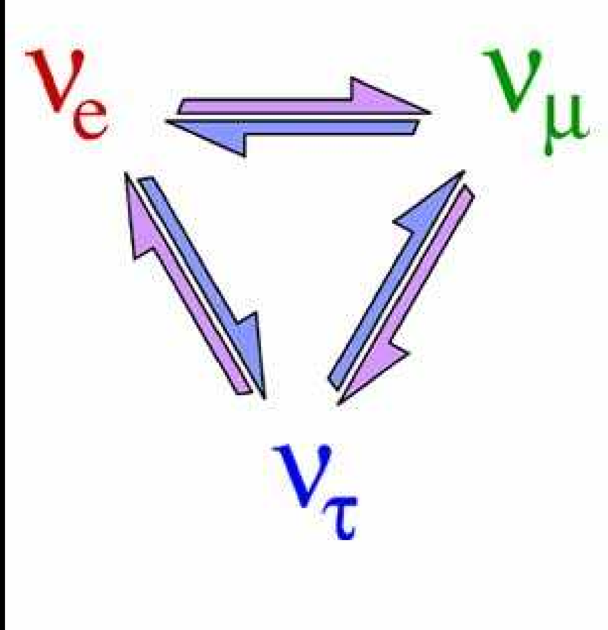
Beyond SM: Empirical Evidence

- **Neutrino Flavor Oscillations**

Solar, atmospheric, and terrestrial data

Strongly suggests: $\exists\, m_\nu \sim 0.1$ eV

$m_\nu / m_e \lesssim 10^{-6}$!

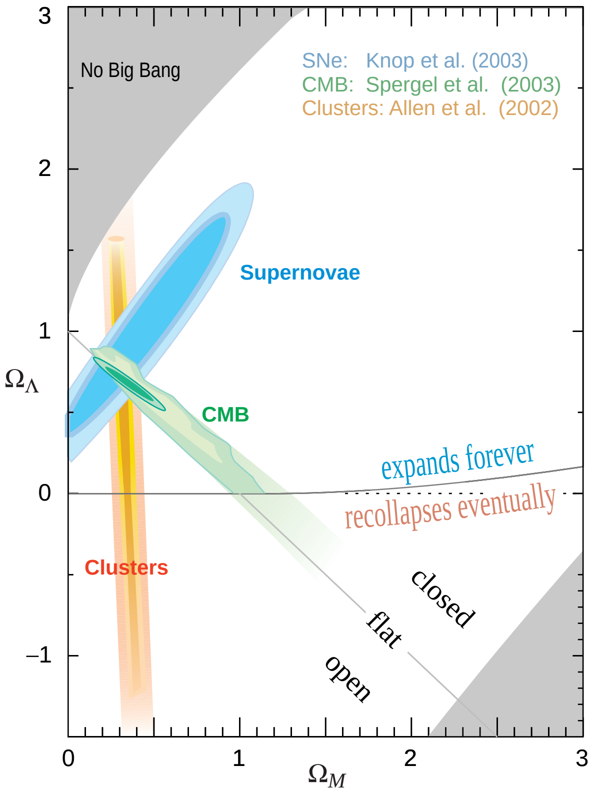


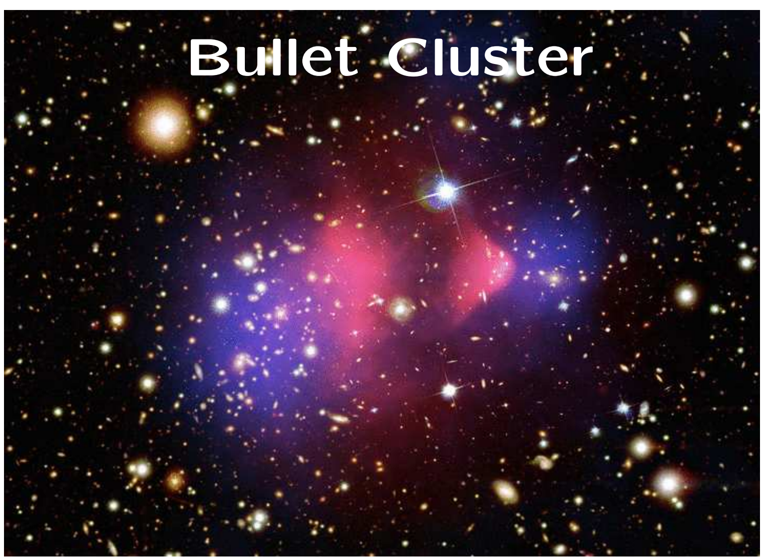
The periodic change of neutrino flavor from one type into another is referred to as neutrino oscillations.

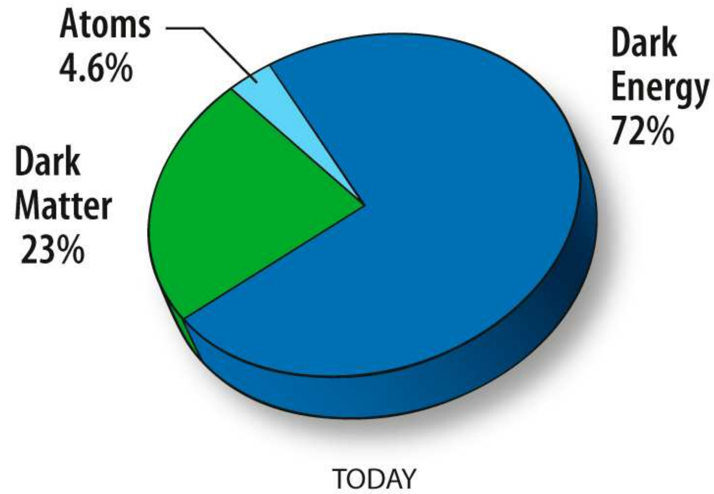
- **Cosmology**

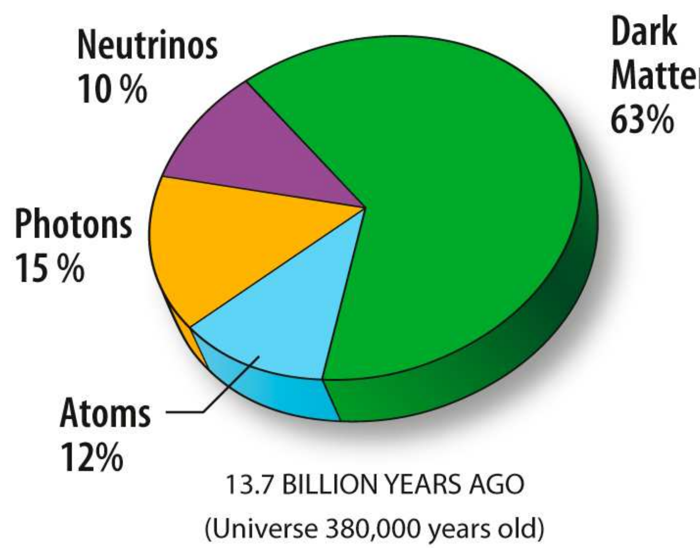
Dark Matter

Good candidates: neutral, stable, $m \sim m_W$.









95% of the universe: unknown!

Cosmic acceleration (DE): could be vacuum energy.

Conceptual Mysetery:
Why is gravity so weak?

Force between e and p in an atom: $\frac{F(\mathtt{Grav})}{F(\mathtt{EM})} \sim 10^{-40}$!

Gravity: the weakest known interaction.

Newton's Constant: $G_N = 6.67 \times 10^{-11}$ m^{3}kg^{-1}s^{-2}

Interaction $\longrightarrow$ mass scale ($\propto$ 1/length). (Heisenberg)

Gravity scale: Planck mass

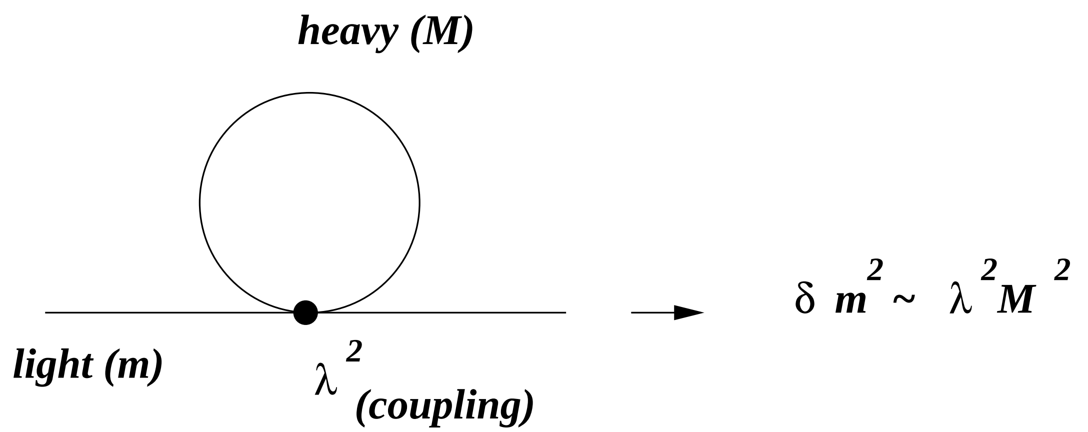
$$M_P \equiv (\hbar c/G_N)^{1/2} \approx 10^{19}\ \mathrm{GeV} \sim (10^{-35}\ \mathrm{m})^{-1}\,!$$

$$M_P \gg m_W$$

Hereafter, $\hbar = c = 1$.

Rephrase the question: Why is $m_W \sim 10^{-17} M_P$?

Is this a problem?



- SM: $m_W \sim \langle H \rangle$.

- Quantum effects: $\langle H \rangle \to M_P$.

$\Rightarrow m_W^2 \sim (100\ \text{GeV})^2$: cancellations to

0.0000000000000000000000000000000001 !

- Conceptually "unnatural" :

The Hierarchy Problem

A much more severe case: Energy density of empty space (10^{-120}).

Cosmological Constant problem.

The Hierarchy Suggests new physics near m_W

- **Strong Interactions near m_W.**

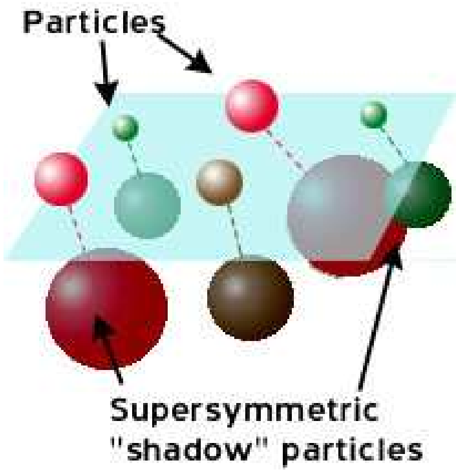
\- m_W from dynamics; *e.g. technicolor*.

$\Rightarrow$ Weak-scale techni-hadrons (analogues of p, ρ, . . .)

- **Supersymmetry: Fermions $\leftrightarrow$ Bosons.**

\- Quantum effects on $\langle H \rangle$ cancel.

\- Spontaneously broken:



Very short distance: Higgs cannot "see" it. (Back to hierarchy.)

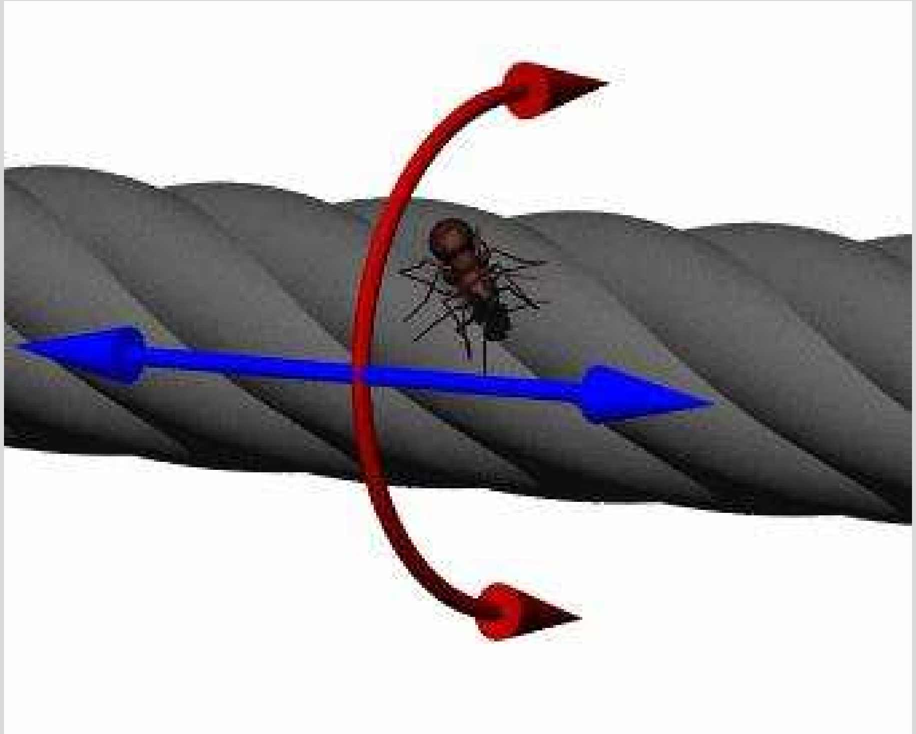
Very long distances: We should "see" it. (We do not.)

$\Rightarrow$ *Superpartners near Higgs mass.*

$\Rightarrow$ LHC Signals, DM candidate.

Extra Dimensions and Hierarchy

- Compact extra dimensions:



Macroscopically “invisible”.

Two Major Classes:

- Large Extra Dimensions. Arkani-Hamed, Dimopolous, Dvali, 1998
- Small but Warped Extra Dimensions. Randall, Sundrum, 1999

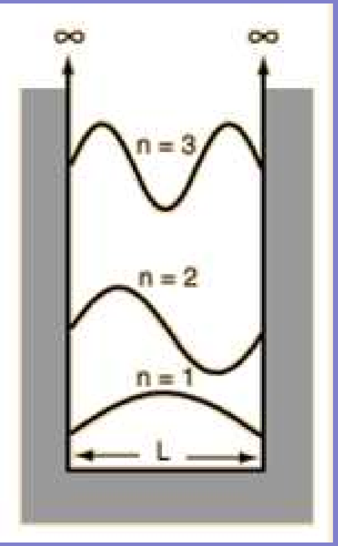
Kaluza-Klein Modes

- Momentum along extra dimensions $\rightarrow$ mass in 4D:

$$p_{(4+n)}^2 = 0 \Rightarrow p_{(4)}^2 - \overrightarrow{p}_{(n)}^2 = 0 \Rightarrow p_{(4)}^2 = \overrightarrow{p}_{(n)}^2 = m^2.$$

- $\overrightarrow{p}_{(n)}$ quantized $\sim 1/R$ (QM particle in a box):

$$|\overrightarrow{p}_{(n)}| \propto \frac{1}{R}, \frac{2}{R}, \cdots$$



- $(4+n)$D field $\rightarrow$ 4D Kaluza-Klein (KK) tower.

- Example: graviton (spin-2 mediator of gravity).

Collider Signal: production and detection of KK particles.

Large Extra Dimensions (LED)

Arkani-Hamed, Dimopoulos, Dvali, 1998

- $(4+n)$D, size R

- SM: 4D, Gravity: $(4+n)$D, scale M_F

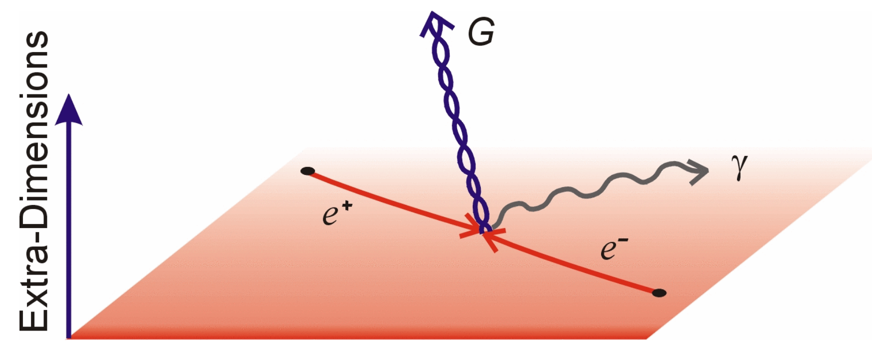
Gauss' law: $V(r) \propto 1/(\boxed{M_F^{2+n} R^n}\, r) \rightarrow 1/(\boxed{M_P^2}\, r)$ in 4D

Higgs stable if $M_F \sim m_W \Rightarrow$ $\boxed{R \gg 1/M_F}$

Gravity "diluted" in extra dimensions

- Light ($\gtrsim 1/R$) graviton KK modes.

Emission and exchange.



- Black holes at $\sqrt{s} \gg M_F\,(m_W)$.

Meade, Randall, 2007: $2 \to 2$ Quantum gravity effects more likely at the LHC.

A Warped Extra Dimension

Randall, Sundrum, 1999

- A slice of AdS_5 (constant negative curvature).

$M_5 \sim M_P$.

- Flat 4D TeV and Planck branes.

Original RS: 4D SM on TeV brane.

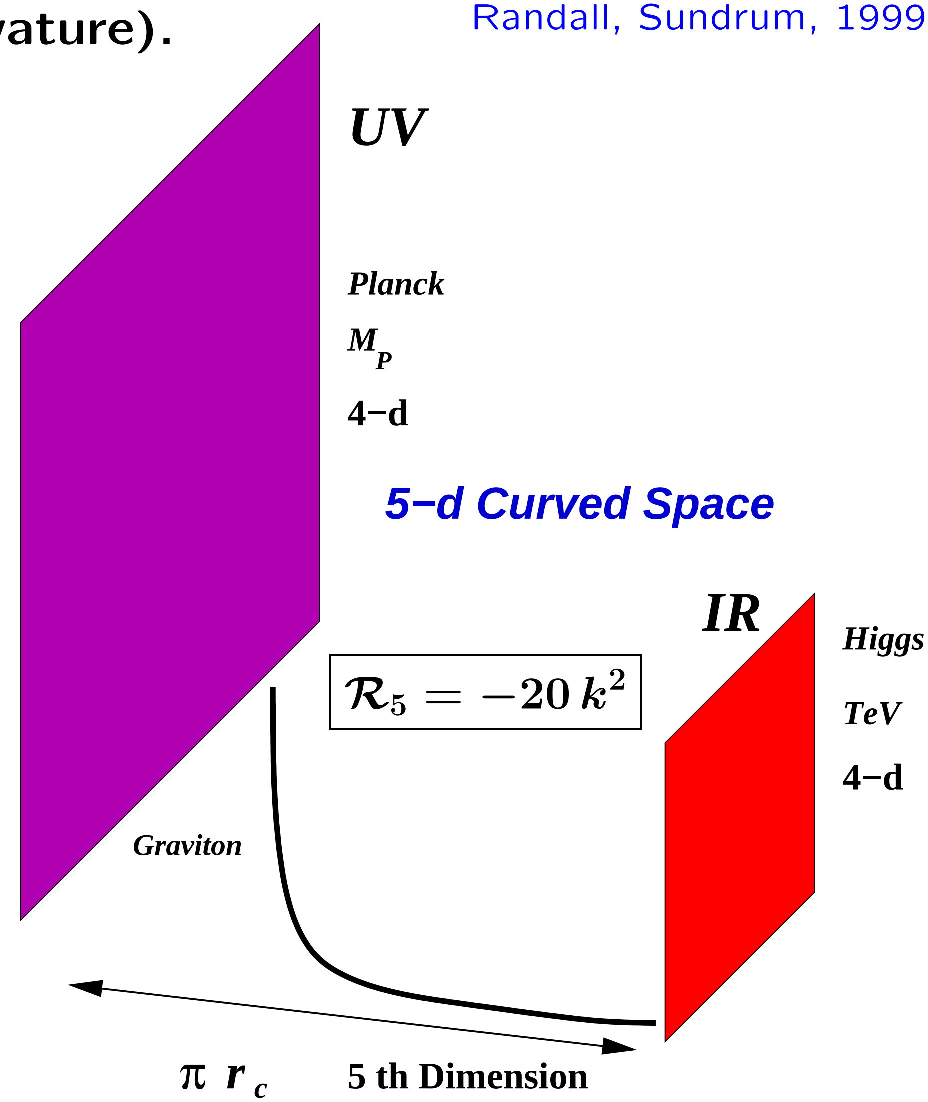
$$ds^2 = e^{-2ky}\,\eta_{\mu\nu}\,dx^\mu dx^\nu - dy^2$$

$k \lesssim M_5$ (curvature scale)

- 4D graviton: Planck-brane localized.

- Redshift ($y = \pi r_c$): $\boxed{M_5 \rightarrow e^{-k\pi r_c} M_5}$

$kr_c \approx 12$: $M_5 \rightarrow m_W$



Natural Hierarchy

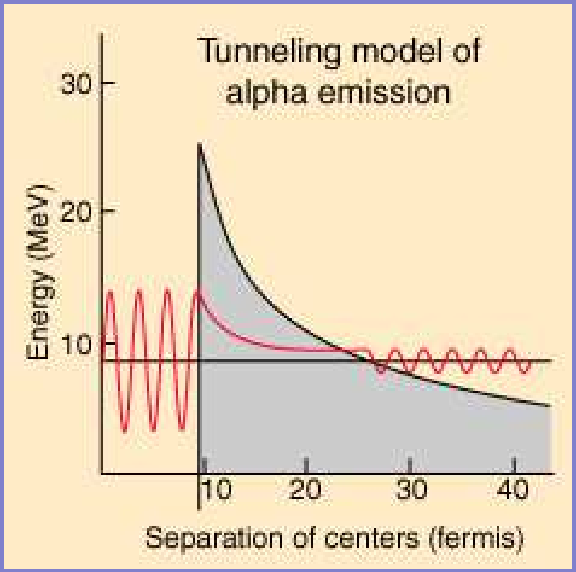
RS Framework: Familiar Concepts

(I) Gravitational redshift in GR: Schwarzschild metric, mass M.

Light emitted at r_1, detected at r_2 $(r > 2M)$: Observed: Pound, Rebka, 1960

$$\frac{\omega_1}{\omega_2} = \frac{g_{00}(r_1)}{g_{00}(r_2)} = \frac{(1-2M/r_2)^{1/2}}{(1-2M/r_1)^{1/2}}.$$

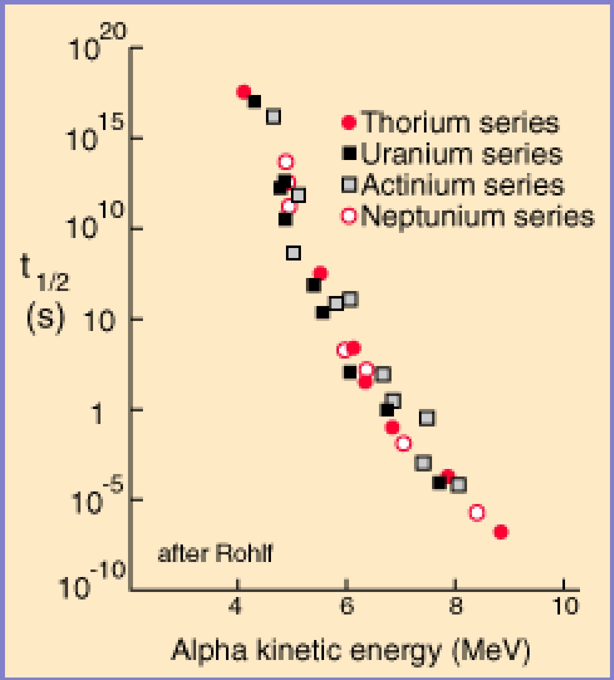
(II) Exponential naturalness: α-decay half-lives.



Over 20 orders of magnitude!

Tunnelling exponential.

Natural hierarchy.



RS Signatures with 4D SM

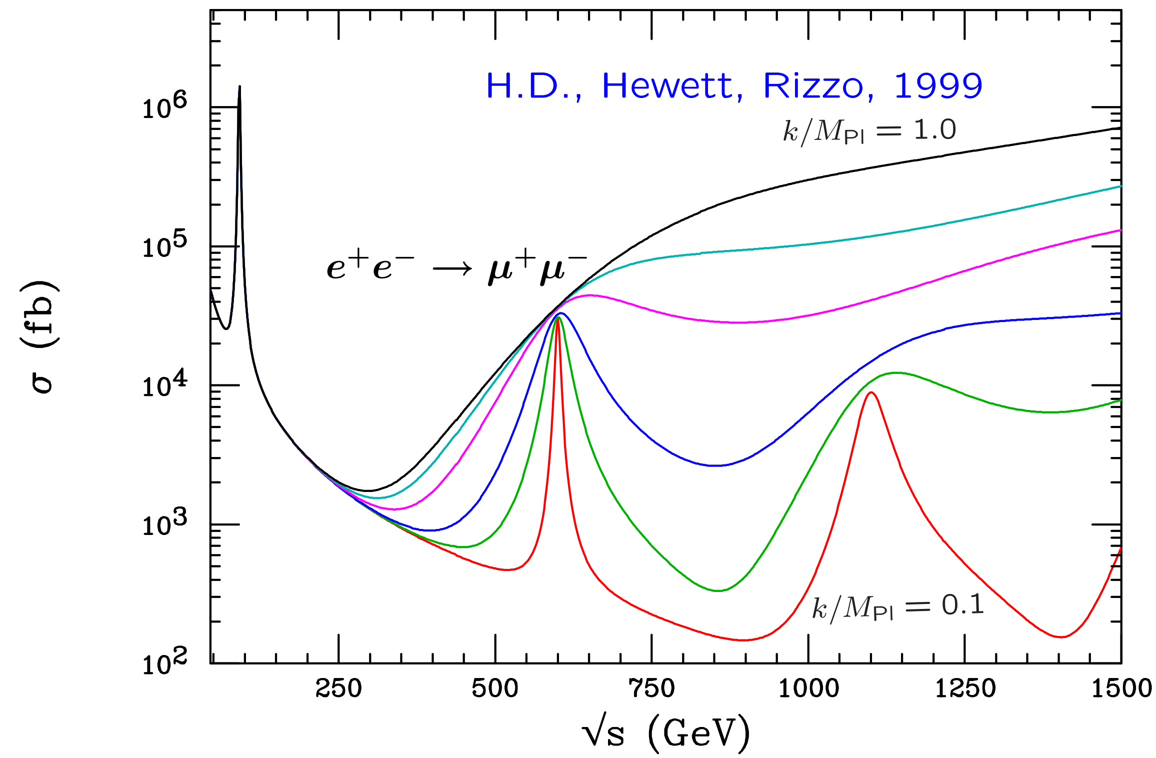
- TeV-scale KK gravitons (*spin-2 resonances*). $m_W \sim 0.1$ TeV

Distinct RS signature

- KK masses $m_n \sim x_n \times$ TeV

$x_n = 3.83, 7.02, \ldots$

- Coupling to SM-brane: $\sim$TeV^{-1}.
- Decay into e^+e^-, $\gamma\gamma$, ...



- Stabilized geometry $\to$ *Radion* scalar

Goldberger, Wise, 1999

- Typically lighter than KK modes.
- Couplings similar to Higgs.

Tevatron Bounds and LHC Prospects

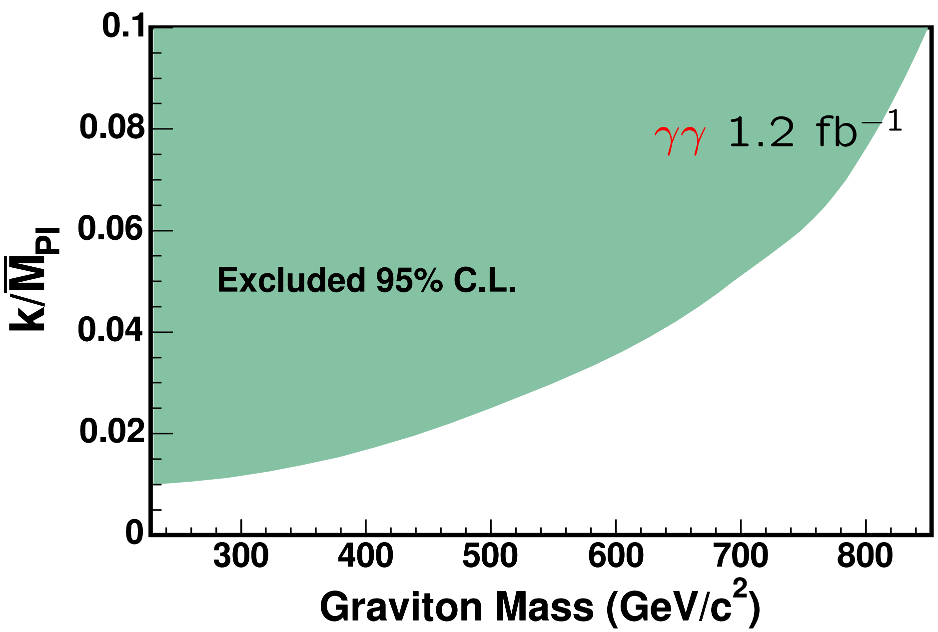
CDF Collaboration (Aaltonen *et al.*)

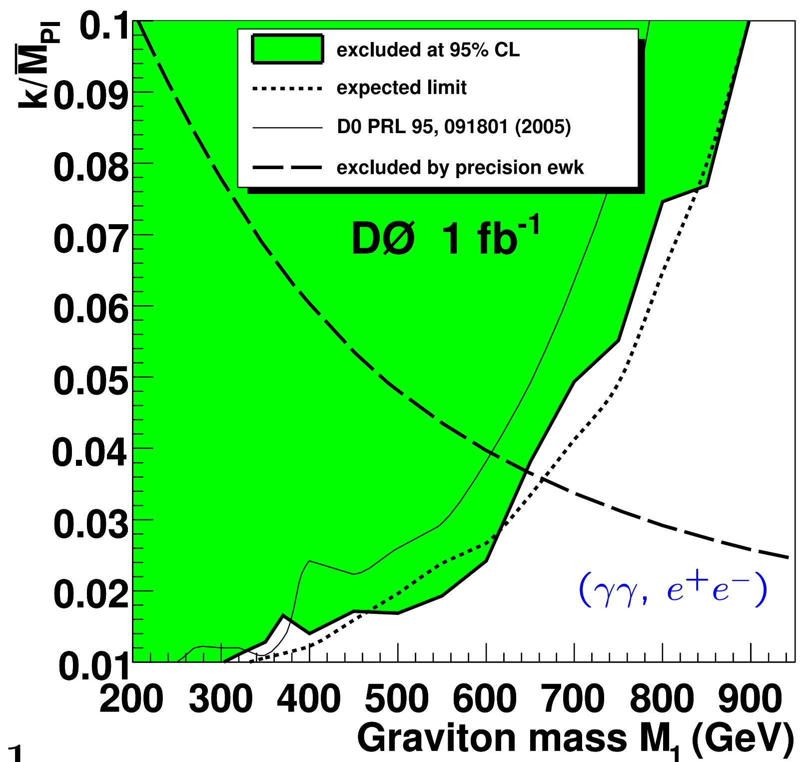
Phys.Rev.Lett.99:171801,2007

[Preliminary (di-muon) 2008 results similar.]

D0 Collaboration (Abazov *et al.*)

Phys.Rev.Lett.100:091802,2008





ATLAS, CMS, 100 fb^{-1}: 3-4 TeV for $k/M_P \simeq 0.1$

Allanach *et al.*, JHEP 0212:039,2002

Belotelov *et al.*, CMS Note 2006/104

The RS Model with 4D SM (1999)

Pros:

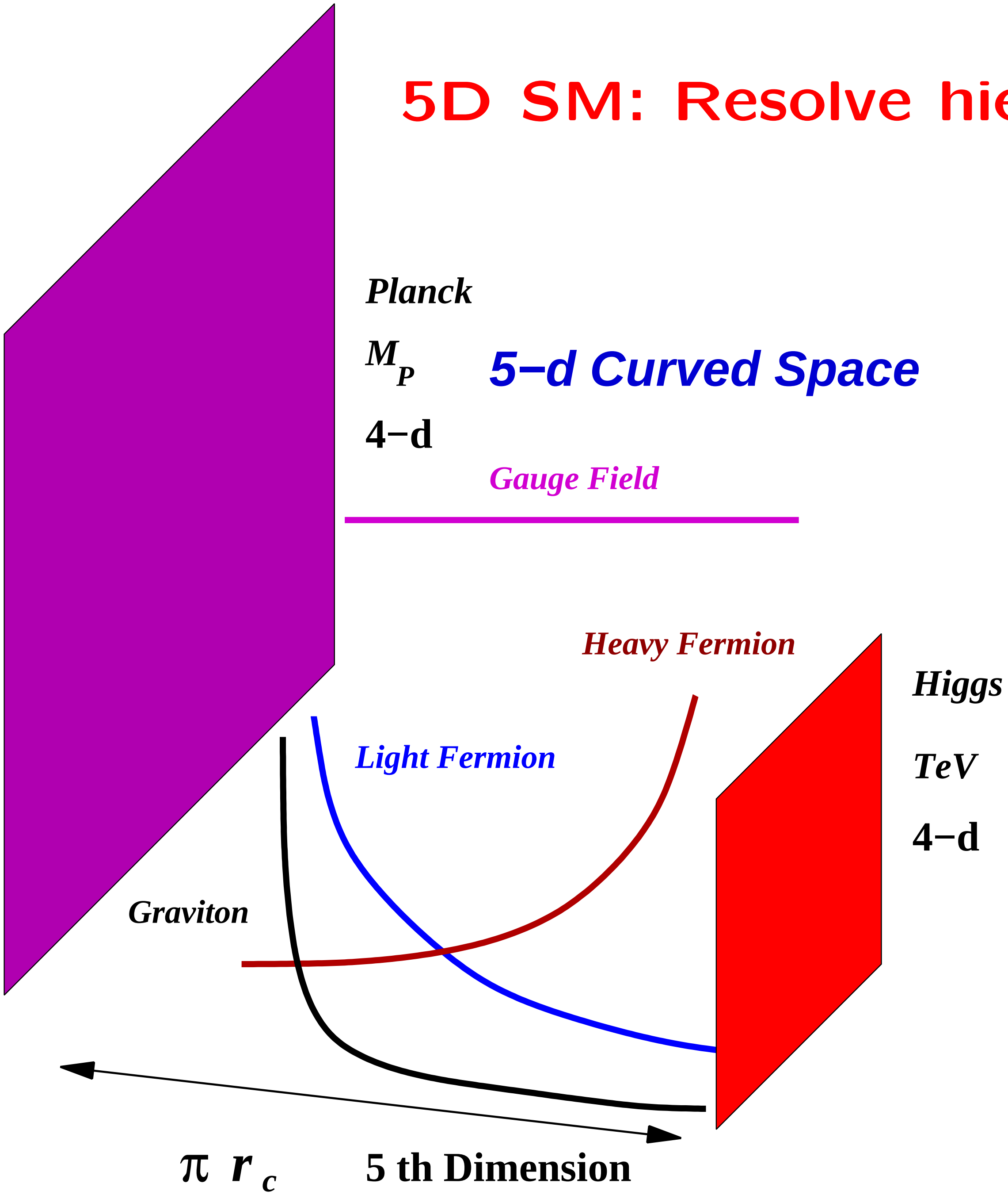
- Natural Planck-weak hierarchy.
- Striking signals.

Cons:

- Flavor still a mystery (like many models).
- Unwanted effects red-shifted to near observable scales.

More technically: low ($\sim$ TeV) cutoff scales $\rightarrow$ FCNC, . . . problems.

5D SM: Resolve hierarchy & flavor puzzles!



- *5D masses → fermion profiles: Light (heavy), UV(IR)-localized.*
- *Unwanted light flavor effects: governed by large* **UV** *scales.*

H.D., Hewett, Rizzo, 1999

Grossman, Neubert, 1999

Gherghetta, Pomarol, 2000

Phenomenology of Hierarchy/Flavor Models

- $\mathcal{O}$(TeV) KK states: IR localized

- Collider signals: more challenging.

- Suppressed (light field couplings):

- Production.

- Clean decay modes, *e.g.* $\mu^+\mu^-$.

- Decay mostly into boosted $t\bar{t}, W_L^\pm, \ldots$.

- Difficult final states.

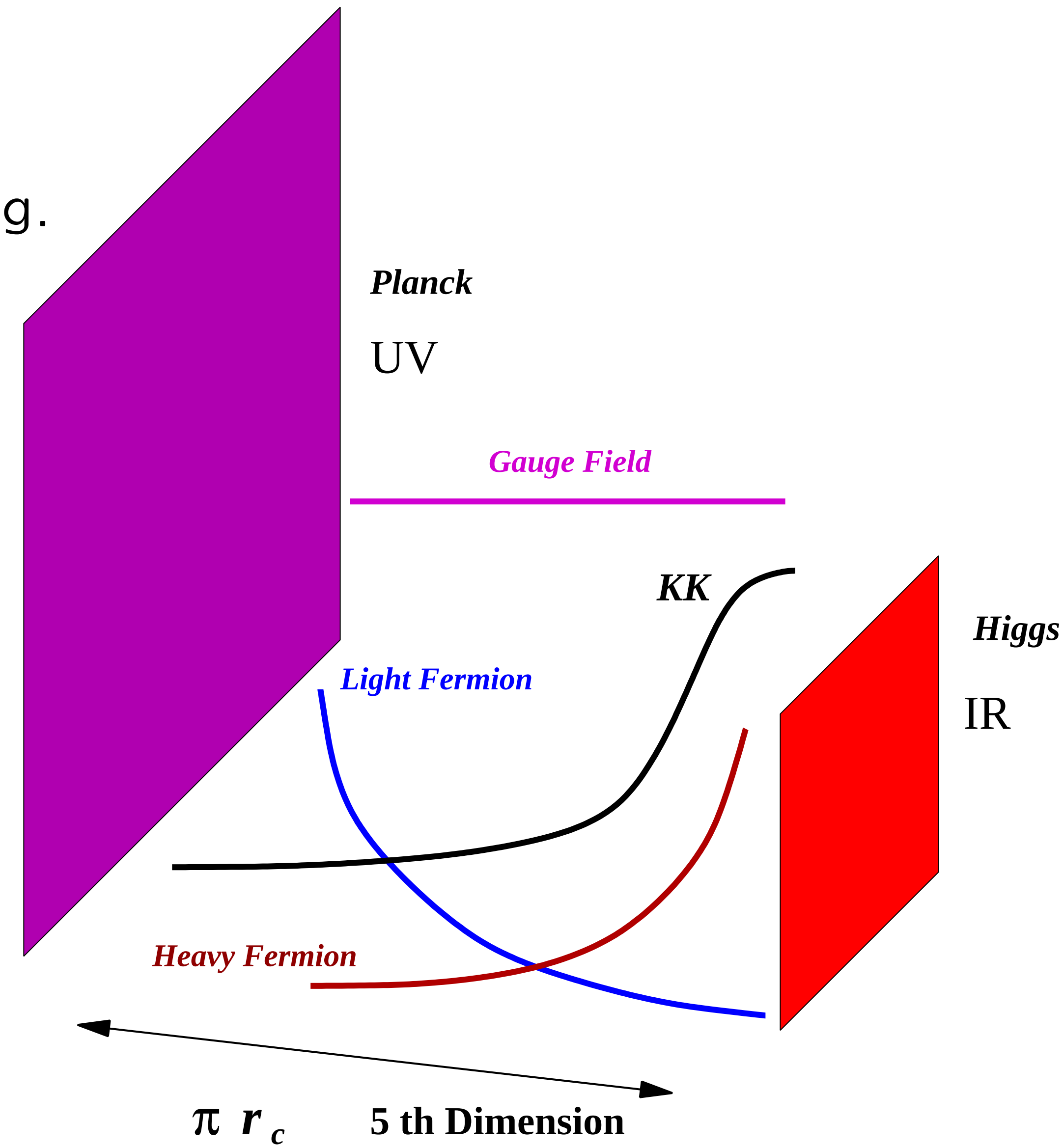
- Large Backgrounds.

E.g., S: $WW(\to jj)$; B: Wj.

- Precision data: $m_{\text{KK}} \gtrsim 3$ TeV.

- Still requires extended 5D symmetries.

E.g., $SU(2)_L \times SU(2)_R \times U(1)_X$.



Agashe, Delgado, May, Sundrum, 2003

Realistic Bulk Flavor: RS@LHC Revisited

- KK gluons: Agashe, Belyaev, Krupovnickas, Perez, Virzi, 2006

- Reach ~3-4 TeV with 100 fb^{-1}. See also: Lillie, Randall, Wang, 2007

- KK gravitons:

Fitzpatrick, Kaplan, Randall, Wang, 2007

- Reach $\lesssim$ 2 TeV with 300 fb^{-1}. Agashe, H.D., Perez, Soni, 2007

- The EW sector: [5D $SU(2)_L \times SU(2)_R \times U(1)_X$]

- Z' (3 neutral states): Agashe, *et al.*, 2007

- Reach $\sim$ 2 TeV with 100 fb^{-1}.

- W' (4 charged states): Agashe, Gopalakrishna, Han, Huang, Soni, 2008

- Reach similar to Z'.

May be improved by better control over reducible backgrounds.

- Direct verification of 5D content may need *NHC*:

- $\sqrt{s} \approx 60$ TeV, $L \approx 1000$ fb^{-1}. H.D., Rizzo, Soni, 2007

Truncated RS Models

- Address smaller hierarchy: $M_5 < M_P$.

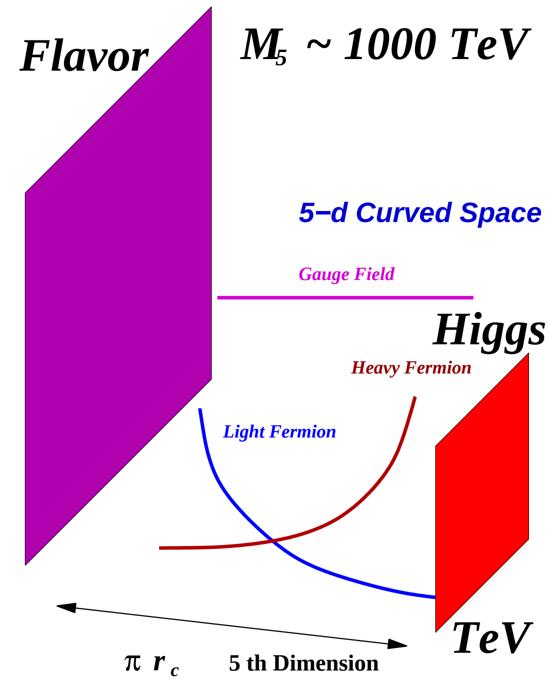
- Truncation: $y \approx \ln(M_P/\text{TeV})/\ln(M_5/\text{TeV})$.

- Example: Model of *flavor* with $M_5 \ll M_P$.

The "Little Randall-Sundrum" Model

H.D., Perez, Soni, 2007.

- A number of unwanted contributions can be suppressed.



- Collider discovery potential much improved.

- *E.g.* Z' discovery in $e^+e^-, \mu^+\mu^-$ channels.

$$\boxed{S \sim y^3,\ S/B \sim y^4}$$

$M_5 \sim 10^4$ TeV $\to y \approx 4$, large enhancement!

The AdS/CFT Connection

Rough Statement:

Certain nD strong interactions related to gravity in AdS$_{n+1}$!

Maldacena, 1997

- Warped models based on AdS$_5$ dual to some 4D strong dynamics.

Arkani-Hamed, Porrati, Randall, 2000

- KK modes $\leftrightarrow$ Composite states

Analogues of ρ, ω,. . . , in QCD.

- Computational framework for strongly-coupled 4D dynamics.

Summary

- Evidence for physics beyond SM: empirical and conceptual.
- Higgs-Planck hierarchy: suggests new physics near m_W.
- Extra Dimensions can shed light on hierarchy.
- Echoes of gravity from other dimensions may emerge at colliders!
- A warped dimension may also explain fermion flavors.
- Hierarchy from gravitational redshift!
- Flavor from geography in a warped dimension.
- Higher dimensional origin for SM.
- Various new states are predicted near LHC reach.
- LHC discovery reach enhanced in truncated models.

Epilogue

Perhaps it was the fall of an **apple** that led **Newton** to the universal law that governs the motion of the heavens. Centuries later, the nature and origin of the forces that brought that apple to **rest** continue to be central questions in fundamental physics. Over the coming years, our quest to understand these forces may lead us back to gravity and into new dimensions of space.

> ...I am induced by many reasons to suspect that they [phenomena of nature] may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards each other, and cohere in regular figures, or are repelled and recede from each other; which forces being unknown, philosophers have hitherto attempted the search of nature in vain; but I hope the principles here laid down will afford some light either to this or some truer method of philosophy.
>
> Sir Isaac Newton
>
> (Preface to Principia)